AD-A039 351 NAVAL POSTGRADUATE SCHOOL MONTEREY CALIF F/G 14/4

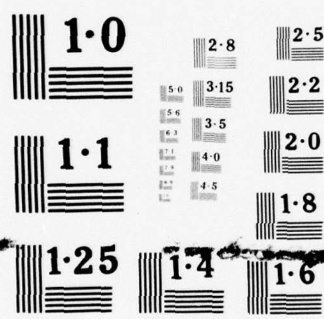
THE POTENTIAL USE OF RELIABILITY GROWTH CURVES IN MANAGEMENT OF--ETC(U)

SEP 76 R G ANDERSON

UNCLASSIFIED NL

1 OF 1
ADA
039351

END
DATE
FILMED
6-77



NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

2
NW

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

The Potential Use of Reliability
Growth Curves in
Management of Weapon Systems

by

Ronald G. Anderson

September 1976

Thesis Advisor: J. W. Creighton

Approved for public release; distribution unlimited.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) 6 The Potential Use of Reliability Growth Curves in Management of Weapon Systems		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis, ~~September 1976~~
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Ronald G. Anderson		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940	11	12. REPORT DATE Sep[redacted] 1976
		13. NUMBER OF PAGES 52 12 53p
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This paper explores the potential use of Reliability Growth Curves as a means by which the program manager can monitor and measure the reliability growth of a weapon system. The present reliability policies associated with weapon system acquisition are reviewed. Examination of three weapon system's Request for Proposals show how these policies are implemented. MIL-STD 785A, which provides the guidelines for reliability programs, is also

cont on p 1473B

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
(Page 1) S/N 0102-014-6601

251 450

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

(cont fr p 1473A)

reviewed and is followed by a discussion of the weaknesses of today's policies. This sets the stage for the presentation of the proposed method that will enable the program manager to control the reliability growth of new weapon systems.

A

The Potential Use of Reliability
Growth Curves in
Management of Weapon Systems

by

Ronald G. Anderson
General Engineer, Pt. Mugu, California
B.S., Northrup Institute of Technology, 1963

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 1976

Author: Ronald G Anderson

Approved by: John W. Creighton, Thesis Advisor

Second Reader

Carl R Jones, Chairman, Department of Administrative Sciences

Academic Dean

ABSTRACT

This paper explores the potential use of Reliability Growth Curves as a means by which the program manager can monitor and measure the reliability growth of a weapon system. The present reliability policies associated with weapon system acquisition are reviewed. Examination of three weapon system's Request for Proposals show how these policies are implemented. MIL-STD 785A, which provides the guidelines for reliability programs, is also reviewed and is followed by a discussion of the weaknesses of today's policies. This sets the stage for the presentation of the proposed method that will enable the program manager to control the reliability growth of new weapon systems.

TABLE OF CONTENTS

I. INTRODUCTION

A. BACKGROUND

Programs for the acquisition of weapon systems are constantly facing new challenges. This is the result of inflation, rising costs and pressures both from Congress and the public. Elmer B. Staats, Comptroller General of the United States in 1974, states [1]:

> "The rising concern of the Congress and the public about increasing costs of new defense weapons is certainly not news. The patience of the public and the Congress has been worn thin by repeated experiences with contractor and Defense Department cost forecasts for new weapons that are unrealistic, and the promises of performance miracles by new weapons that later proved unattainable."

In addition, today's defense strategies and tactics, designed to meet the rapidly changing international situations, require weapon systems of increasing complexity which demand an increase in the performance requirements and environmental operating conditions. This requirement for complex weapon systems has created a technology explosion which threatens to doom systems under development to technical obsolescence before they become operational. These problems were cited in 1972 by former Deputy Secretary of Defense, David Packard [2]:

> "Cost overruns were the most visible symptoms of the troubled new weapon development situation but there were other problems too. Most programs took far too long from original conception until weapons were delivered to the operational military forces. As a result, many weapons, particularly those involving electronics and other fast-moving technology, were out of date by the time they were available."

To compound the problem, even after exorbitantly high cost and unnecessarily long development time, many of the new

devices did not have the reliability that is needed for military use.

With these various factors affecting the acquisition of weapon systems, how does one achieve a highly reliable weapon system? Management in the Department of Defense and contractors have increased their efforts to improve the reliability of weapon systems. However, despite these efforts, the reliability of weapon systems continues to be disappointing. Studies throughout the Department of Defense have been and continue to be made in an effort to find ways to improve reliability.

In May 1972, the "Mean Time Between Failure" Improvement Study Group, headed by RADM K. R. Wheeler, SC USN, conducted a major study for the Navy on reliability and maintainability improvement. The resulting report, better known as the "Wheeler Report" [3] concluded that those equipments found unreliable in the fleet simply did not have reliability designed in from the beginning. The report cited the following specific conditions existing in 1972 which were considered to be crucial factors influencing reliability in Navy acquisition efforts.

Sufficient time and dollars omitted from budgetary submissions

Unenforcible reliability goals in contracts and no enforcible reliability requirements

Poor or nonexistent reliability testing procedures

Insufficient reporting systems to identify unreliable equipments in the fleet

Pressure for attaining specified performance goals which lead to trade-offs that though not explicit, aggregate to lower reliability

Poor documentation of trade-offs between reliability and performance

In 1973 the Air Force also conducted a study [4] in which they found 37 possible deficiencies that could affect reliability of the weapon systems. The following is a listing of those that have a relation to the acquisition of weapon systems:

Contractor has no incentive to overdesign reliability in equipment

No provisions made for reliability growth during development

Changes in mission profiles of operational equipment

Operational equipment used in environments for which they were not designed

Contract reliability requirements changed to goals or not enforced

As a result of these Governmental studies, new reliability policies were issued. One emphasis being that quantitative reliability requirements will be stated in "Request for Proposals" (RFP). The policies further state that these requirements will be minimum acceptable, realistic and achievable. The effects of these new policies are still questionable. In the article "Improving R & D Management Through Prototyping," David Packard states [5]:

"A serious problem that troubles all of our recent major programs is reliability. Numerous directives, specifications, and other requirements have been placed on all major development programs to attempt to improve the reliability of new weapons. Very little improvement, if any, has come from this effort and very large sums of money have been spent.

"Reliability cannot be achieved by adhering to detailed specifications. Reliability cannot be achieved by formula or by analysis. Some of these may help to some extent but there is only one road to reliability. Build it, test it, and fix the things that go wrong. Repeat the process until the desired reliability is achieved. It is a feedback process and no other way."

B. PURPOSE

Reliability has become an issue of major concern in the acquisition of new weapon systems and today's reliability policies do not provide the program manager with the needed visibility during the weapon system's development. The purpose of this paper is to propose a method by which the program manager can monitor and measure the reliability growth of the weapon system as it proceeds through its life cycle from initial design to the end of development.

II. WHY A RELIABILITY PROGRAM

One of the major forces that demands a reliability program is the ever increasing cost of weapon systems. This is well recognized by the Department of Defense as evident by their emphasis on the "Design to Cost" concept of which reliability is an essential element. This is further amplified by CDR Hollister, USN, and R. Shorey of the Office of the Assistant Director (Electronics) [6]:

> "In design to a cost development, reliability and maintainability are especially important considerations. There is concern that a developer, motivated to provide the highest level of system performance possible at a target cost, may implicitly trade reliability and maintainability for greater performance...
>
> "Minimum reliability and maintainability requirements are established along with other minimum acceptable performance specifications. These are treated as major system performance parameters during performance verification."

In his book "Reliability Mathematics," Bertram L. Amstradter states [7]:

> "The importance of obtaining highly reliable systems and components has been recognzied in recent years. From a purely economic viewpoint, high reliability is desirable to reduce overall costs. The disturbing fact that the yearly cost of maintaining some military systems in an operable state has been as high as ten times the original cost of the equipment emphasizes this need...
>
> "The need for and importance of reliability have been reflected in the constantly increasing emphasis placed on reliability by both government and commercial industry."

Other factors that demand reliability improvement are safety, schedule delays, inconvenience, and combat effectiveness in the fleet. Willis J. Willoughby, Deputy Chief of Naval Material for Reliability and Maintainability, states [8]:

"The Navy, like other Military Services, is faced with less-than-desired combat effectiveness levels and rising life cycle costs. This situation exists because reliability has not been properly specified and pursued; rather, the Navy has relied heavily on integrated logistic support."

III. PRESENT RELIABILITY POLICIES

A. POLICIES

Various instructions that have been issued provide the best overview of the present policies governing reliability and the acquisition of weapon systems.

1. SECNAVINST 5000.1

SECNAVINST 5000.1, System Acquisition in the Department of the Navy, was issued in March 1972 and contains as Enclosure (1), DOD Directive 5000.1. This instruction now establishes all major policy and management principles for the acquisition of weapon systems. In spite of the fact that reliability is now a major issue in the acquisition of weapon systems, no reference to reliability can be found in the 40 pages of this instruction. In Section II, Conduct of Program, reference is made to Enclosure (4) of the instruction which is a list of applicable documents. This list contains no more than 56 different instructions that have some bearing on the acquisition of weapon systems. Buried in this list is SECNAVINST 3900.36A, which is the instruction governing Reliability and Maintainability.

2. SECNAVINST 3900.33A

SECNAVINST 3900.33A, Initiation of Engineering and Operation Systems Development, was issued in September 1968. This instruction established the Navy policies for the acquisition of weapon systems during the Conceptual Formulation and Contract Definition phases. The following statements pertaining to reliability were contained in this instruction:

System Trade-offs: Trade-offs will be used to obtain optimum balance between total cost, schedule, and operational effectiveness (reliability) for the system.

Conceptual Phase: Quantitative reliability and maintainability goals and demonstration concepts.

Engineering Development: Quantitative reliability and maintainability specifications for the system and major subsystems and proposed test plans to demonstrate their achievement.

This instruction has been superseded with the issuance of SECNAVINST 5000.1.

3. OPNAVINST 5000.42A

OPNAVINST 5000.42A, Weapon Systems Selection and Planning, was issued in March 1976. This instruction establishes the policies for identifying operational requirements (OR) and conducting management reviews during system acquisition. The instruction makes only two references to reliability. One being that reliability is to be considered in establishing system performance goals. The second reference is the following statement:

From the outset, planning will accord high priority to simplicity in design and toughness of management, including trade-offs and contractual provisions, to ensure a high degree of reliability and maintainability.

4. SECNAVINST 3900.36A

SECNAVINST 3900.36A, Reliability and Maintainability (R & M) for Naval Material, was issued in June 1970. This instruction establishes the R & M policies for the Navy and assigns responsibility for its achievement. With regards to the acquisition of weapon systems, the following is found in this instruction:

Basic Concept: Reliability techniques are based on the fact that failure will occur and they focus attention on means to minimize the effect of failure. The required R & M is

justified in that it supports mission requirements. Therefore, it must be considered throughout the life cycle of the system.

Policy: During the conceptual and development phases of new systems, each program will include a minimum acceptable R & M value based on operational need. A specified confidence level is normally required for the R & M demonstration.

Responsibilities:

a. The Chief of Naval Operations is responsible for;

Ensure that requirements documents include numerical R & M requirements and "Goals" or "Objectives" shall not be used in lieu of R & M requirements.

Evaluate proposed decreases in R & M requirements for impact on operational characteristics where development is unable to economically achieve R & M minimum values.

b. The Chief of Naval Material is responsible for;

Ensure that quantitative R & M requirements are responded to in proposal for industry.

Determine adequacy of each contractor's R & M program for achieving and demonstrating R & M requirements.

B. REQUEST FOR PROPOSALS

To obtain a first hand knowledge of how these policies are implemented, three Request for Proposals (RFP) were reviewed.

1. <u>Harpoon Weapon System</u> [9]

a. Reliability Standards listed

(1) MIL-STD 721: Definition of Effectiveness Terms
(2) MIL-STD 756: Reliability Prediction
(3) MIL-STD 781: Reliability Tests
(4) MIL-STD 785: Reliability Program Plan
(5) MIL-STD 1304A: Reliability Reports
(6) MIL-R-22732: Reliability Requirement for Shipboard and Ground Electrical Equipment

b. Reliability Section

(1) Definition: A definition for reliability was provided in the RFP and it was the one cited in MIL-STD 721.

(2) Reliability Requirements: The requirements stated in the RFP were of two types, a reliability probability and a Mean Time Between Failure (MTBF). Numerical numbers were stated, however, in the listing below only the reliability probability (R) or the MTBF will be noted.

Sub System	Min Acceptable Reliability Req't	Reliability Design Objective
Missile		
Freeflight	R_1	R_2
Standby	$MTBF_1$	$MTBF_2$
Ready	$MTBF_1$	$MTBF_2$
Storage	R_1	R_2
Aircraft Command and Launch	$MTBF_1$	$MTBF_2$
Shipboard Command and Launch	$MTBF_1$	$MTBF_2$

The RFP further amplifies the requirements by providing the following:

Missile Freeflight Reliability: They shall have a freeflight reliability of R_2 as a design objective and R_1 as a minimum acceptable value. The missile shall be able to operate under a degraded mode. Free-flight is defined as the missile profile from launch to target intercept.

Aircraft Equipment Reliability: Each new item of equipment for aircraft command and launch shall have a MTBF (numerically specified) design goal and a MTBF (numerically specified) minimum acceptable value.

Shipboard Equipment Reliability: Same type of statement as for the aircraft equipment.

(3) Reliability Program Plan: With regards to a reliability program plan, the RFP states the following:

The contractor shall provide and maintain a reliability program that is acceptable to the government.

The contractor shall use design techniques described in paragraph 5.2.1 of MIL-STD 785A to the extent practicable during the design phase to assure that the reliability requirements will be met during the weapon systems development phase.

The contractor shall conduct a reliability analysis of the Harpoon Weapon System during the design phase in accordance with paragraph 5.2.2 and all subparagraphs of MIL-STD 785A.

2. VFAX Airborne Weapon System [10]

a. Reliability Standards listed

(1) MIL-STD 721: Definition of Effectiveness Terms
(2) MIL-STD 756: Reliability Prediction
(3) MIL-STD 785: Reliability Program Plan

b. Reliability Section

(1) Reliability Requirements: Quantitative requirements are stated for two phases of the weapon system.

Mission reliability: The mission reliability, expressed as the probability that the Airplane Weapon System can perform all the mission functions successfully, shall equal or exceed 0.XX as a goal.

Refly reliability: The refly reliability, expressed as the probability that the Airplane Weapon System can be returned to full operating capability without corrective maintenance between missions, shall equal or exceed 0.XX based on a t-hour mission duration with 0.XX as a goal.

(2) Reliability Program Plan: The request for proposal states that a reliability program will be established in accordance with MIL-STD 785 and the reliability specification appendix of the request for proposal. The appendix provides amplification of various sections of MIL-STD 785 and in some cases specific instructions as to how and what will be included in the program.

A section of the reliability specification appendix states what testing is required demonstrating the reliability of the weapon system. The tests are classified in two categories, preproduction and quality conformance.

The preproduction test is to determine if the Airplane Weapon System has met the quantative reliability requirements. Whereas, the quality conformance test is to determine if the Airplane Weapon System offered for acceptance has met the quantitative reliability requirements.

3. AEGIS Weapon System [11]

a. Reliability Standards listed

(1) MIL-STD 721: Definition of Effectiveness Terms
(2) MIL-STD 756: Reliability Prediction
(3) MIL-STD 781: Reliability Tests

(4) MIL-STD 785: Reliability Program Plan
(5) MIL-R 22732: Reliability Requirements for Shipboard and Ground Electrical Equipment

b. Reliability Section

(1) Definitions: The RFP provides definitions for System Effectiveness, Inherent Availability and Operational Availability.

(2) Reliability Requirements: The requirements stated in the RFP are of two types, those being availability and reliability.

Shipboard System Availability: The minimum acceptable shipboard system inherent availability shall be at least 0.XXX over a t-month deployment period under the following conditions:

(a) The system will be in the standby or operate mode of operation at least 75 percent of the time.

(b) The MFAR radar is to be considered a primary search radar.

(c) The system is considered available when; It is down for preventive maintenance, provided the capability to return to full operation within t-minutes is retained. Five out of six illuminators are available and remainder of the system segments are providing specified performance.

Shipboard System Reliability: The MTBF for the system, including test sets and built-in monitoring devices, but excluding missiles shall be not less than t-hours.

(3) Reliability Program Plan: The reliability program plan requirement has been divided into three phases.

<u>CD Phase A</u>: The contractor shall submit as part of his proposal a Preliminary Reliability and Maintainability Plan identifying the work to be performed during Engineering Development (ED) and its relationships to and expected impact on the designs formulation process.

<u>CD Phase B</u>: The contractor shall, during this phase, expand the plan into a comprehensive program for execution during engineering development. This program plan shall comply with requirements of MIL-STD 785 and MIL-STD 470. The plan shall present detailed procedures by which reliability and maintainability will be measured, evaluated, and controlled throughout ED.

<u>ED Phase</u>: The contractor shall develop a Production R & M Plan. This plan shall establish and describe those detailed procedures by which inherent R & M characteristics are monitored and retained during production.

The RFP further breaks down the reliability program to detailed task requirements as follows:

Requirements Interpretation, Allocation and Feasibility Analysis
Predictive Assessments
Design Selection
Design Analysis
Parts and Materials Selection and Control
Parts Qualification
Reliability Quality Assurance
R & M Data Reporting, Analysis and Feedback
Design Qualification Tests
Acceptance Tests

(4) Policies: To obtain maximum availability without sacrificing any of the high performance requirements, the following policies have been set forth:

Maximum utilization of proven components--the design trade-offs must favor proven reliability over potential savings in weight, space or costs of unproven components.

Standardization--Standardization of components, printed circuit cards, modules and subassemblies must be maximized.

Redundancy and Fault isolators--the system design must be optimized for maximum reliability and minimum down time through the use of redundancy, automatic systems monitoring and simplified fault isolators.

C. MIL-STD 785A

Title: Reliability Program for Systems and Equipment Development and Production.

Purpose: To establish uniform criteria for a reliability program and provide guidelines for the preparation and implementation of a reliability program.

Outline: This standard provides guidelines as to what shall be included in a reliability program plan. Major headings that are to be in this program plan are:

Reliability Management
Reliability Design and Evaluation
Reliability Testing and Demonstration
Failure Data
Production Reliability
Status Reports

As one reviews these various sections of the MIL-STD, it is noted that the context is in generalities and no specific detailed guidance is given. In the Program Review section (5.1.4) and the Design Review sections (5.2.7), it states that progress will be reviewed at appropriate stages of development and production to evaluate achievement of the reliability requirements. However, no information is given as to how the progress will be monitored or to what criteria it is to be measured against, other than the numerical requirement (which is the number to be achieved at the end of development).

D. SUMMARY

A review of the policies has shown that very little guidance is given in terms of reliability and the acquisition of a weapon system. Guidance can be summed up in the following statement:

> A minimum acceptable numerical requirement and a Reliability Program requirement will be stated in the RFP.

The three RFP's that were reviewed showed that this is exactly what was stated. As to the completeness and detail of the requirements, this depends upon the program manager who is responsible for the context of the RFP, as can be seen by the variance in the RFP's. In each of the RFP's, three to six military standards are referenced, but only one (MIL-STD 785A) is cited in the reliability section. In the VFAX and AEGIS RFP's, additional detail is given to supplement MIL-STD 785A. However, there is no information given in any of the three RFP's as to how the reliability of the system will

be monitored or measured during its development. As noted in the review of MIL-STD 785A, which is cited in all the RFP's, no information is contained as to monitoring or measurement of reliability during development.

IV. MANAGEMENT AND RELIABILITY GROWTH

A. INTRODUCTION

"Reliability Prediction" can be defined as an estimate of the performance we can expect of the equipment on its originally scheduled delivery date.

It is essential in treating the subject of reliability to understand basic concepts relating to techniques for prediction and control of reliability. The following contributions from persons knowledgeable in the field are intended to provide this understanding.

> "The formal process of Reliability Prediction is based on the exponential distribution of random, statiscally independent failures, occurring as a result of some inherent nonsystematic propensity of things to fail. The mathematics associated with this process requires that failure rates of each constituent item be known and constant with time. The resulting failure rate "prediction" is independent of time. This is a fatal flaw, because we observe achieved failure rate to be a function of time. That being the case, the prediction can only represent an ultimate limiting value. Such a value might be of some use if it could be depended upon, but it cannot, because performance is exceeding predicted values every day...
>
> "The numbers game has outlived its usefulness to the point of severely interfering with our ability to do the real job. In today's explosive development of new parts, and equipment of astonishing capability--where successive models are each a new generation of development--classical reliability prediction is nearly useless: The numbers it produces are rarely relevant to the solution of any of our problems." (Ernest Codier, General Electric Co.) [12]

> "Many popular techniques for the analysis of reliability consider the problem only at a single point in time. Such techniques certainly yield value information. However, a complete treatment of system reliability requires careful consideration of the time variations introduced by design changes or modifications in maintenance practices." (J. T. Duane, General Electric Co.) [13]

"Experience has shown that reliability values reported from field service are generally lower--often much lower--than those predicted by design analysis or demonstrated by laboratory testing. This has led to optimistic projections of operational effectiveness and ownership cost. It can also lead managers down a "primrose path" during development, since predictions and demonstrations indicate that reliability requirements are being met." (Robert Parker, Deputy Director Defense Research and Engineering) [14]

"...Despite special management efforts and major technological improvements, Air Force avionics equipment still does not demonstrate high reliability. This shortcoming is compounded by the fact that the reliability predictions which are formulated during equipment design, refined during development, and tested during formal laboratory demonstrations, infer equipment reliability that is often significantly greater than what is actually achieved when the equipment is operationally employed." (Lt Gen Robert Marsh, USAF, Vice Commander, Air Force Systems Command) [15]

As noted by the various comments, the conventional reliability analysis techniques, in particular "reliability prediction," are not providing the desired reliability in weapon systems. Reliability prediction provides a useful data point. However, it is being used in dealing with time and design changes, but it does not provide the manager with a useful tool to monitor the reliability growth of the weapon system during its development. In the implementation of the present reliability policies (Section III), the manager is in the dark as to the reliability of the weapon system until development is completed. In order to insure that the weapon system reliability will meet the contractual requirement, the program manager must have some type of yardstick by which he can visually measure the reliability growth of the weapon system during development. This yardstick must also provide information as to when design changes are required, and when the system has met its contractual requirement. Barlow states:

"It is common practice, during the development of a system to make engineering changes as the program develops. These changes are generally made in order to correct design deficiencies and, thereby, to increase reliability. This elimination of design weaknesses is what we mean by reliability growth." [17]

To summarize the above, reliability growth is that growth observed in reliability as the weapon system progresses along its life cycle. A visual representation is presented in Figure 1.

B. THE YARDSTICK

Present policy requires that a reliability program be established for a new weapon system in accordance with MIL-STD 785A. This military standard provides for a sound reliability program for the attainment of the reliability requirement. However, it does not provide the means to monitor or measure the reliability growth of the weapon system. It is proposed that a "Reliability Growth Curve Prediction" be contractually imposed as part of the Reliability Program Plan to provide the means to monitor and measure reliability.

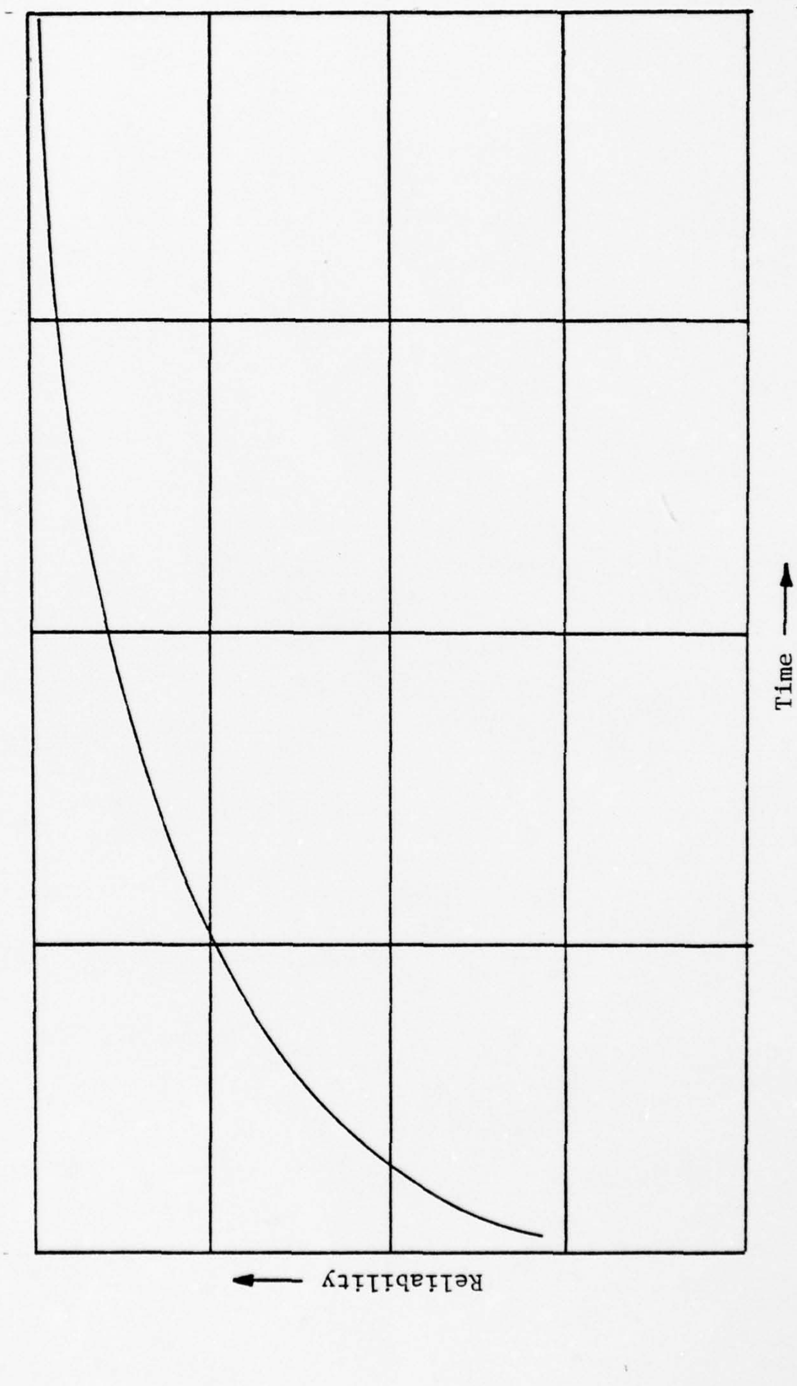
C. RELIABILITY GROWTH CURVE

1. What is It? Amstradter states:

"...reliability growth is, in reality, a discrete function which occurs, hopefully, each time a design change is made. [16]

2. Is It New?

Reliability growth is not new. Much has been written about it, as can be noted in Appendix A, Bibliography on Reliability Growth. It has only been in recent years that it has come into its own and has been recognized as a useful



TYPICAL RELIABILITY GROWTH CURVE

FIGURE 1

management tool. Although the major emphasis has been only to monitor reliability growth during development testing, more thought is being given to use it as a forecasting method.

> A reliability growth model is an analytic tool useful in determining the time required to develop an acceptable product. The model monitors the progress of the development program and can be used to forecast the time required to achieve the reliability goal if the program were to be modified. [18]

> This technique should be useful to the reliability engineer in the monitoring of development progress to insure that reliability specification requirements are achieved. A further desirable characteristic would be for techniques to provide for continuing extrapolation from current status to some future result... This technique is known as reliability growth curve methodology. [19]

3. Two Types of Growth Curves

Reliability growth curves can be classified into two categories; Assessment and Apportionment [20].

a. Assessment--When reliability-growth equations and curves are prepared after a program is well into the development phase and thereby utilize actual test data to arrive at appropriate numerics, growth analysis becomes primarily an assessment process.

b. Apportionment--If a growth curve is prepared to depict expected levels of reliability achievement and to provide a continuum of time-oriented goals, it can be classed as an apportionment procedure.

4. Models

There are several reliability growth models, each of which is valid in its own right. The purpose of this paper is not to present the various models and how to apply them,

but to show that reliability growth curves have a place in management. However, to acquaint the reader with reliability growth models, Appendix B provides a review.

5. The Purpose of Reliability Growth Models

The use of reliability growth curves has several potential purposes. They include:

a. Monitoring the reliability progress of the system as it proceeds through development.

b. If a reliability growth curve was predicted, it provides a means to measure the actual growth of the system.

c. It provides for forecasting of reliability in the short term.

d. Provides the means to measure the effectiveness of design changes.

e. Aids in defining design problems and what their impact on reliability will be.

f. Aids in the allocation and reallocation of resources to achieve requirements on schedule and within constraints.

g. Aids in determining requirements for future procurements.

h. Provides a useful communication vehicle for high level management.

i. Aids in planning the development program and to control its progress as the design matures.

6. Is It Applicable?

The best method to show the applicability of reliability growth curves is to cite several examples. The

examples will be divided into the two categories of reliability growth modeling; assessment and apportionment.

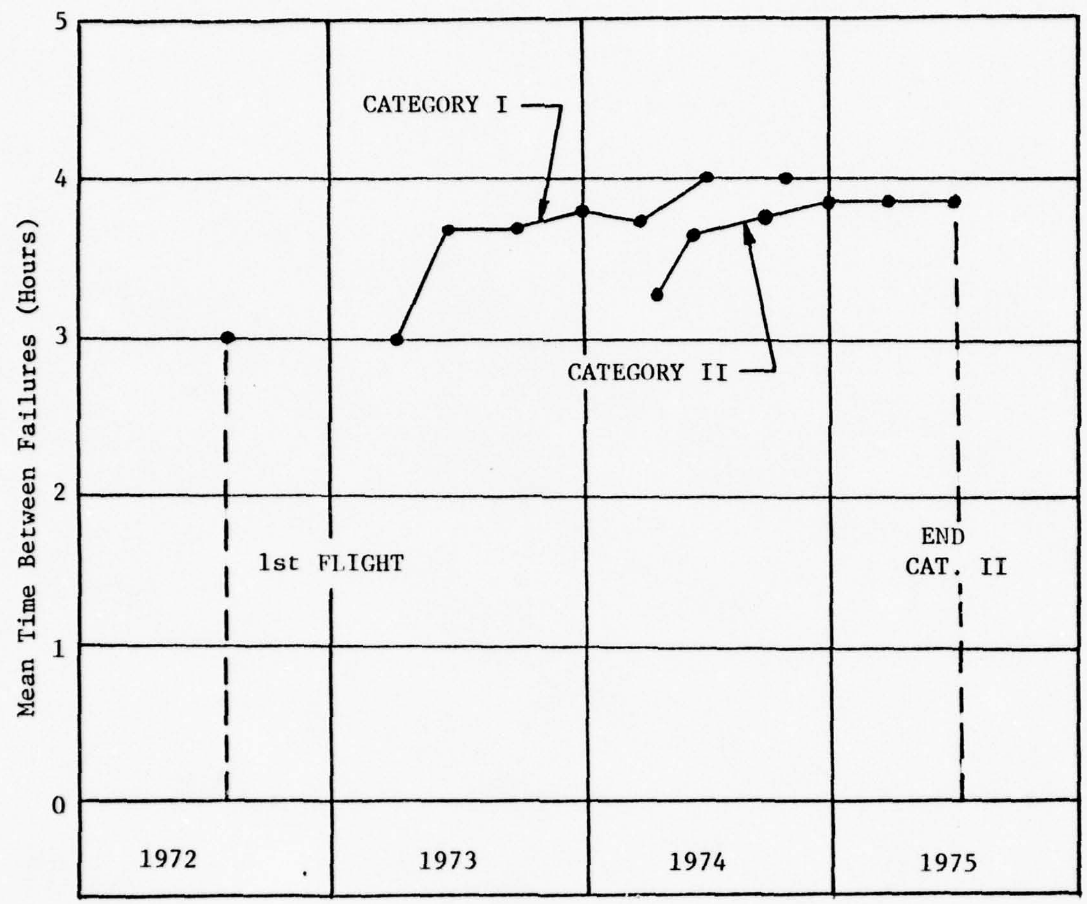
a. Assessment Examples

(1) F-15A Aircraft [21]. The reliability program for the F15A did not call for reliability growth modeling. The reliability requirements were typical of today's policies, i.e., MTBF and a reliability program plan. As part of the reliability program, data were collected, analyzed and plotted. This plotted data (Figure 2) shows the reliability growth of the aircraft during development testing.

It should be noted that the growth curve is not continuous from Category I (contractor evaluation) to Category II (Air Force evaluation). The major contributing factor for this discontinuity is the change in operational environment. This is one of the considerations that must be recognized in using reliability growth modeling.

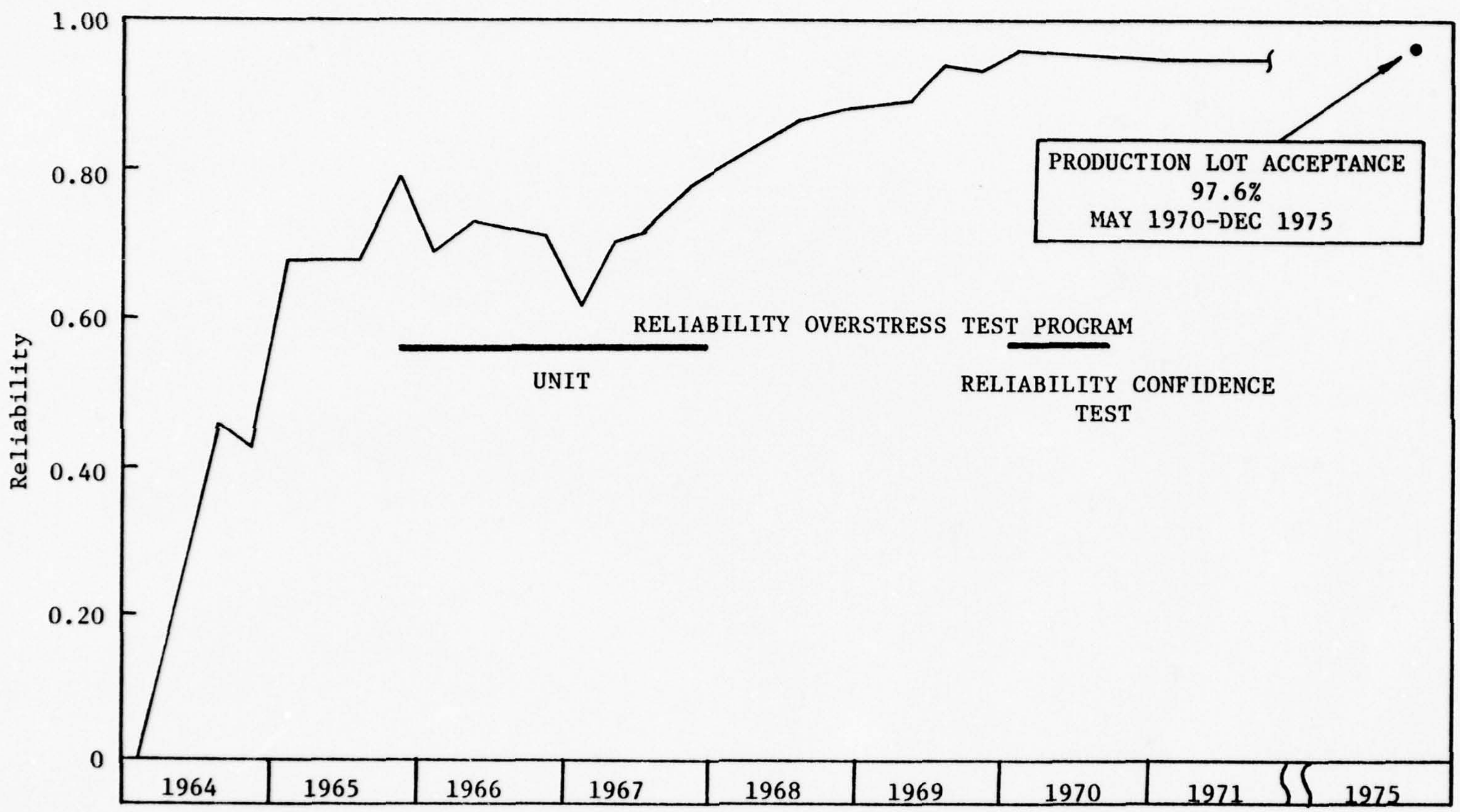
(2) TOW Weapon System [22]. The TOW weapon system is a heavy assault weapon for the U. S. Army. The reliability requirements for this program were based on present day policies. However, a strong emphasis was stressed in the "find and fix" and "overstress" test approach to reliability. Although reliability growth modeling was not a contractual requirement, a plot of reliability growth was maintained throughout the program (Figure 3).

(3) F-111A Aircraft [23]. The reliability program for the U. S. Air Force F-111A aircraft was conducted under present day policies. To assure that the requirements



F-15A MTBF GROWTH

FIGURE 2



TOW MISSILE RELIABILITY GROWTH

FIGURE 3

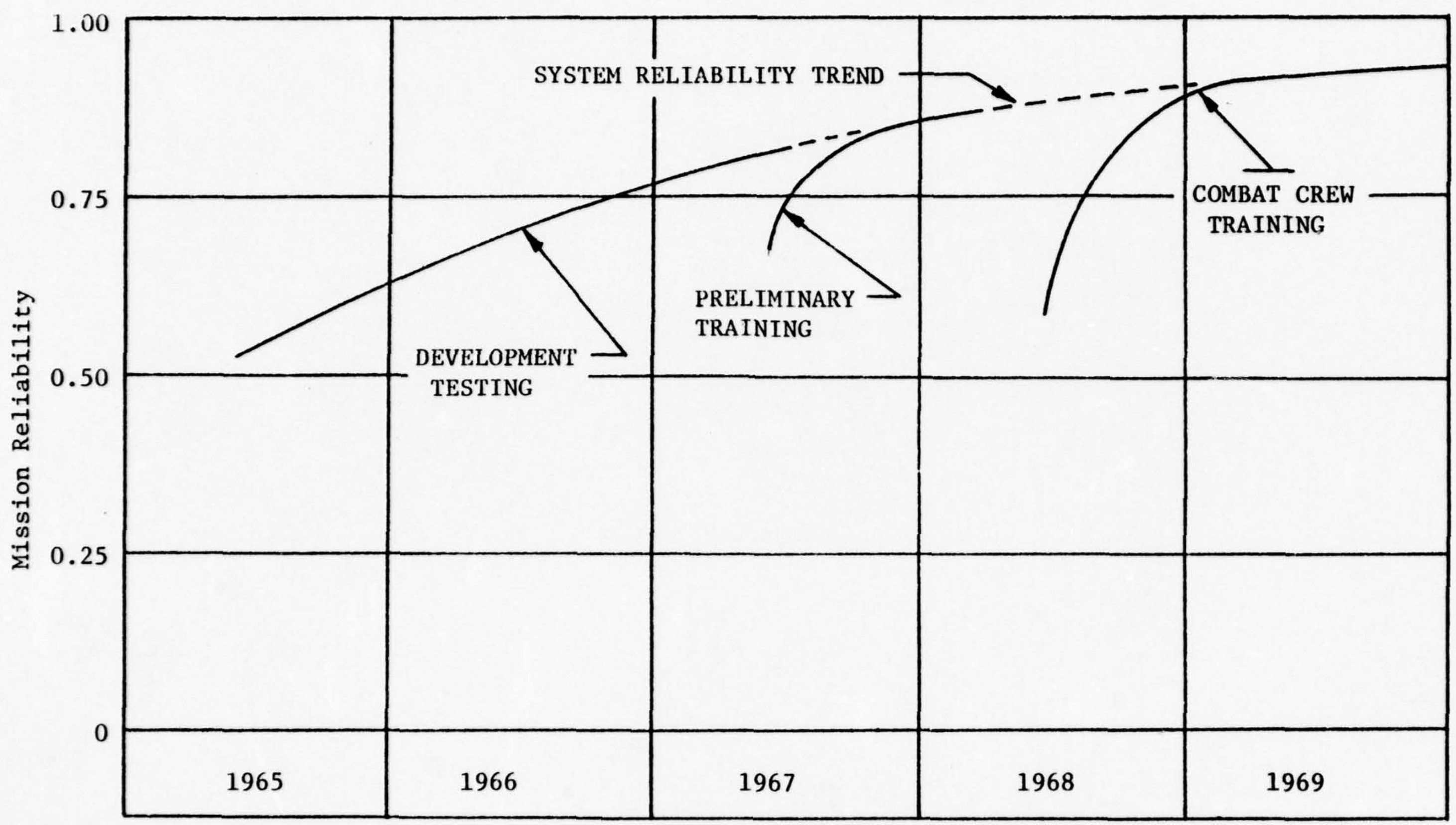
were obtained, a rigorous reliability program was imposed on the contractor. Reliability growth prediction was not part of this program; however, data were plotted to show the reliability growth of the aircraft during its development (Figure 4).

b. Apportionment Examples

(1) C-141 Aircraft [24]. The U. S. Air Force reliability requirement for the C-141 was as follows: The contractor shall plan and conduct a comprehensive reliability program in accordance with the requirements of Weapon Systems Specification MIL-R-26674, Reliability Requirements for Weapon Systems.

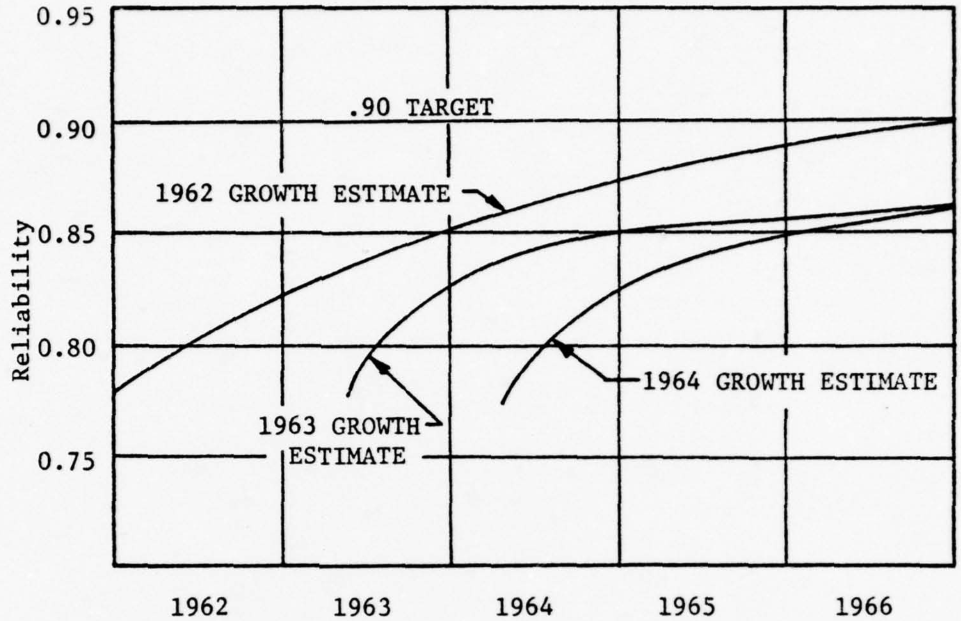
Although the Air Force did not specify a numerical reliability requirement, the contractor established a design goal and performed a prediction analysis to show projected growth to this goal. As the program progressed, predictions were continually updated which resulted in adjustment to the growth curve (Figure 5). As the program progressed through development, observed growth was plotted against the predicted growth curve (Figure 6). This visual representation served as a basis for program reviews and direction for the contractor and the Air Force.

(2) SATCOM Terminals [25]. Reliability growth prediction was not imposed as a contractual requirement, but the Army used the Duane and Weibull reliability growth models to make reliability management decisions. These growth models helped to plan the growth of reliability in the development program and to control its progress as the design matured.



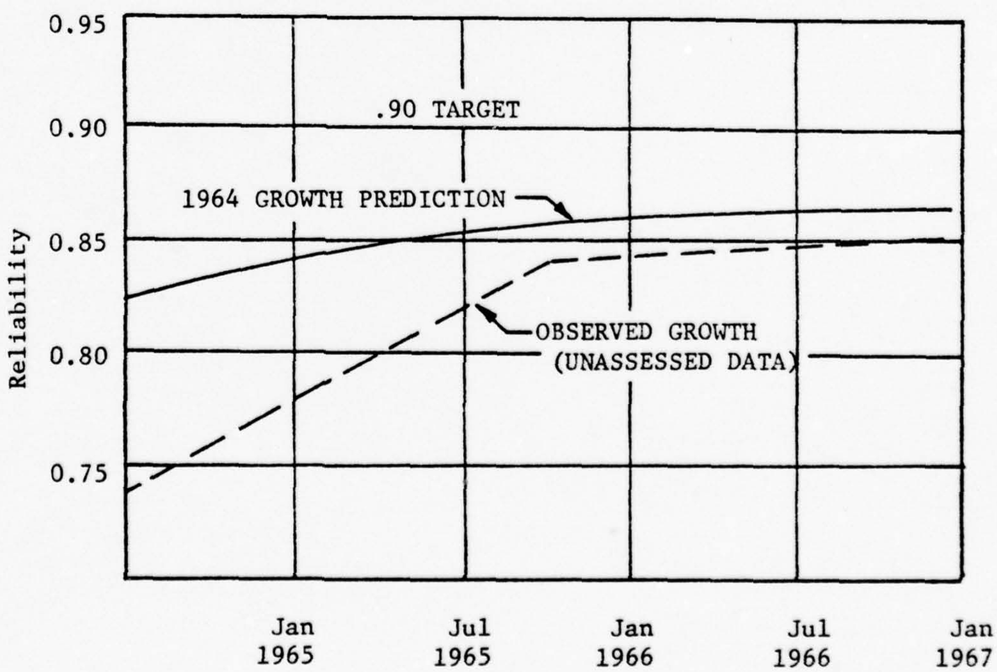
F-111A ACHIEVED MISSION RELIABILITY TREND

FIGURE 4



C-141A RELIABILITY PREDICTIONS

FIGURE 5



C-141A RELIABILITY GROWTH

FIGURE 6

The authors of this article summed up the use of this technique in the following statement:

> "The Duane and Weibull growth curves were used to determine requirements for future buys, provide management visibility for reliability and make decisions regarding test termination."

(3) SM-2 Missile [26]. To meet the contractual MTBF requirement, the contractor established a three-phase reliability program. One phase of this program is "Reliability Growth Monitoring." The procedure that the contractor set up to accomplish this phase was to plot a predicted growth curve that the system was expected to take during its development. The observed data will be plotted against this prediction to provide the impetus for additional action if it appears that the MTBF requirement might not be met. This approach is being taken by the contractor mainly due to another program in which the MTBF growth was plotted and found to be a useful management tool. In a conversation with J. C. Bear [27], he commented that General Dynamics is finding this technique very useful and feels that the potential is there for a very powerful management tool.

D. THE MANAGEMENT TOOL

It has been shown that a potential management tool exists in the use of Reliability Growth Curves. Although the majority of the interest to date has been the assessment of reliability growth, interest is beginning to stir in its use as an estimator of reliability growth of a weapon system. This is evident by contractual requirements now being imposed by

the U. S. Army on new weapon system developments, such as their Stinger program [28].

Present day policies do not provide the program manager visibility as to the reliability growth of the system. The manager does not become aware that the system, in its present design, will not meet the requirements until it is well into demonstration testing. With a predicted reliability growth curve, the program manager has the means by which to measure actual growth and to aid in decision making as to design changes and testing of the system.

E. IMPLEMENTATION

1. Requirement

The requirement for a "Reliability Growth Curve Prediction" should be part of the Reliability Program Plan requirement of the RFP. The requirement could take one of two forms:

a. The Navy with their knowledge of the new weapon system design and development time constraints, could submit the desired Reliability Growth Curve to which the contractor could respond as they presently do with the MTBF requirement.

b. The Navy could require that the contractor submit a "Reliability Growth Curve" as part of their reliability program plan.

In either case, because of its sensitivity depending upon the model used and the factors involved in predicting the curve, the final Reliability Growth Curve Prediction will be a negotiated item between the Navy and the contractor.

2. Pit-Falls

In that Reliability Growth Curve Prediction would be a new management technique, pit-falls should be expected in the early stages. All factors that affect the prediction and the exact sensitivity to the different models can only be learned with use. The following is a listing of several factors that must be considered in selecting the appropriate model and the use of Reliability Growth Curve Prediction.

a. Complexity of the weapon system in that it will have a definite bearing on expected failure rate.

b. Schedule time alloted for development of the system. (Short time, you would expect to see a rapid growth; long time, a more gradual growth.)

c. The various environments that the system is subjected to during development. (Laboratory, contractor field testing, customer testing, etc.)

d. Definition of failure: To avoid discontinuities in the growth curve, failure definition must remain constant [27].

e. Number of expected failures: This would have a bearing in selecting the model that would provide the best growth fit for the system.

V. CONCLUSIONS

The program manager, today, has no means available to him to provide visibility with regards to reliability growth. Reliability prediction provides the manager with the potential maximum value at that point in time when the prediction is made. Reliability demonstration provides the manager with the actual value at the time when the test was conducted. Neither of these two methods provides the manager with the answer to: "Is the weapon system going to meet the reliability requirement?"

The "Reliability Growth Curve Prediction" would provide the manager with insight as to how the weapon system should meet the reliability requirement. And when actual data are plotted and compared to the predicted curve, it would provide the manager insight to the question: "Is the weapon system going to meet the reliability requirement?"

APPENDIX A

BIBLIOGRAPHY ON RELIABILITY GROWTH*

1. Amstradter, Bertram L., Reliability Mathematics, McGraw Hill, 1971, p 220. #

2. Aerojet-General Corp., Solving a Reliability Growth Equation, Report No. LRP-233, Contract AF04 647 521, IV, AD-285 725, September 1961, Aerojet-General Corporation, Sacramento, California.

3. Barlow, R.E., Proschan, F., Scheuer, E.M., Maximum Likelihood Estimation and Conservation Confidence Interval Procedures in Reliability Growth and Debugging Problems, Report No RM-4749-NASA January, 1966, RAND Corporation, Santa Monica, California.

4. Barlow, R.E., Scheuer, E.M., Reliability Growth During a Development Testing Program, Report No RM-4317-1-NASA, October 1965, RAND Corporation, Santa Monica, California. Also Technometrics, Vol 8, 53-60, 1960.

5. Barr, D.R., A Class of General Reliability Growth Prediction Models, Report No NPS-55BN8031A, 40p, AD-831 652, March 1968, Naval Postgraduate School, Monterey, California. Also Operations Research, Vol 18, No 1, 52-65, January 1970.

6. Bear, J.C., Approach to Reliability for the SM-2 Missile, 1973 Annual Reliability and Maintainability Symposium, (IEEE Catalog No 73CH 0714-6R), p 79, January 1973. #

7. Bowling, T.C., Relationships of Hazard Rate Distributions to Reliability Growth and Confidence Computations, Annuals of Reliability and Maintainability, Vol 4, 705-718, 1965.

8. Breipohl, A.M. and McCormick, W.C., Bayesian Estimation of Time-Varying Reliability, Annuals of Assurance Sciences, 347-351, July 1968.

9. Bresenham, J.E., Reliability Grwoth Models, Technical Report No. 74, 64p, Contract NONR225 53, AD-605 993, August 1964, Stanford University, Applied Mathematics and Statistics Laboratories, California.

10. Chernoff, H. and Woods, W.M., Reliability Growth Models-Analysis and Applications, February 1962, CEIR, Los Altos, California.

11. Codier, E.O., Reliability Growth in Real Life, Proceedings of 1968 Annual Symposium on Reliability, (IEEE Catalog No 68 C 53-R), 458-469, January 1968.

12. Codier, E.O., Reliability Prediction--Help or Hoax?, Proceedings of 1969 Annual Symposium on Reliability, (IEEE Catalog No 69C8-R) 383-390, January 1969.

13. Codier, E.O., Reliability in the Third Generation, Proceedings of 1971 Annual Symposium on Reliability, (IEEE Catalog No 71C2-R) 129-132, January 1971.

14. Corcoran, W.J., Read, R.R., Modeling the Growth Of Reliability-Extended Model, UTC 2140-ITR, 15 November 1966, United Technology Center, Sunnyvale, California.

15. Corcoran, W.J., Read, R.R., Comparison of Some Reliability Growth Estimation and Prediction Schemes, UTC 2140-ITR Addendum, June 1967, United Technology Center, Sunnyvale, California.

16. Corcoran, W.J., Read, R.R., Study of the Reliability Growth Implications of Subsystem Versus Full Assembly Testing, UTC 2140-FR, November 1968, United Technology Center, Sunnyvale, California.

17. Corcoran, W.J., Weingarten, H., Estimation of Reliability After Corrective Action on Observed Failure Modes, Special Projects Office, Department of the Navy, Washington D.C.

18. Corcoran, W.J., Weingraten, H., ZEHNA, P.W., Estimating Reliability After Corrective Action, Management Science, Vol 10, 786-795, July 1964.

19. Cox, Tony D. and Keely, John, Reliability Growth Management of SATCOM Terminals, 1976 Annual Reliability and Maintainability Symposium, (IEEE Catalog No 76RM038), p 218, February 1976. #

20. Duane, J.T., Learning Curve Apporach to Reliability Monitoring, IEEE Transactions on Aerospace, Vol 2, No 2, 1964.

21. Dubman, M.R., Sherman, B., Estimation of Parameters in a Transient Markov Chain Arising in a Reliability Growth Model, Contract AF 33(615)-2818, AD 686 817, 55p, January 1969, AD 698 973, 15p, March 1969, Rocetdyne, Canoga Park, California.

22. Earnest, C.M., Estimating Reliability After Corrective Action, A Bayesian Viewpoint, Master's Thesis, 32p, AD 487 411, May 1966, Naval Postgraduate School, Monterey, California.

23. Fink, R.W., Screening for Reliability Growth, Proceedings of 1971 Annual Symposium on Reliability, (IEEE Catalog No 71C2-R), 316-320, January 1971.

24. Fox, B.L., A Bayesian Approach to Reliability Assessment, Report RM 5084-NASA, August 1966, RAND Corporation, Santa Monica, Calif.

25. Gross, A.J., Kamins, M., Reliability Assessment in the Presence of Reliability Growth, Report No RM 5346-PR, Contract F44620-67-C-0045, 65p, AD 659 773, September 1967, RAND Corporation, Santa Monica, California.

26. Hamiton, D.O., and Ness, W.G., Aircraft Reliability Growth Characteristics, 1969 Annual Symposium on Reliability, (IEEE Catalog No 69 C 8-R), p 465, January 1969. #

27. IBM Federal Systems Division, Some Comments on the "Duane" Failure Rate Equation, Report No IBM 71-351-001, 8p, AD 884 690, August 1971, Electronics Systems Center, Owego, New York.

28. Jayachandran, Toke and Moore, Louis R., A Comparison of Reliability Growth Models, IEEE Transactions on Reliability, Vol R-25, No 1, p 49, April 1976. #

29. Kamins, Milton, Jet Fighter Accident/Attrition Roles in Peacetime: An Application of Reliability Growth Modeling, RM 5563-PR, N68-2423, Contract No F44620-67-C-0045, 38p, AD 667 784, March 1968, RAND, Corporation, Santa Monica, California.

30. Kreuze, F.J., Growth Curves-A Pratical Management Tool, Proceedings of 1972 Annual Reliability and Maintainability Symposium, (IEEE Catalog No 72 CH 05 77-7R), 430-436, January 1972.

31. Larson, H.J., Bayesian Methods and Reliability Growth, Report No NPS TR/RP 78, 33p, AD 653 460, March 1967, Naval Postgraduate School, Monterey, California.

32. Larson, H.J., Conditional Distribution of True Reliability After Corrective Action, Report No NPS TR/RP 61, 18p, AD 629 084, January 1966, Naval Postgraduate School, Monterey, California.

33. Lloyd, D.K., Lipow, M., Reliability: Management: Methods and Mathematics, Prentic-Hall, Inc, Englewood, New Jersey, 1962, 331-338.

34. Locks, M.O., Optimum Effort for Reliability Growth, A Bayesian Approach, Research Report RR 64-53, 1964, Rocketdyne, Canoga Park, California.

35. Madansky, A., Peisakoff, M.P., THOR and ATLAS In-flight Reliability Growth, Research Memorandum No RM 2598, 17p, Contract No AF 499 (368) 700, AD 318 298, 22 June 1960, RAND Corporation, Santa Monica, California.

36. Perkowski, N., Hartvigsen, D.E., Derivations and Discussions of the Mathematical Properties of Various Candidate Growth Functions, Report No CRA 62-8, 38p, AD 349 304, October 1962, Aerojet-General Corporation, Azusa, California.

37. Pollock, S.M., A Bayesian Reliability Growth Model, Technical Report/Research Paper No 77, AD 663 279, June 1967, U.S. Naval Postgraduate School, Monterey, California. Also IEEE Transactions on Reliability, Vol R-17, No 4, December 1968.

38. Read, R.R., A Remark on the Barlow-Scheuer Reliability Growth Estimation Scheme, Technometrics, Vol B, No 1, 199-200, February 1971.

39. Selby, J.D., Miller, S.G., Reliability Planning and Management-RPM, AES Publication SI 471, September 1970, ASQC/SRE Seminar, Niagara Falls, New York.

40. Sherman, B., Consistency of Maximum Likelihood Estimators in Some Reliability Growth Models, Contract AF 33(615)2818, 33p, AD 641 146, May 1966, Rocketdyne, Canoga Park, California

41. Sherman, B., Locks, M.O., Design, Testing and Estimation in Complex Experimentation, II, Reliability Growth Processes-Estimation Theory and Decision, Theoretic Formulations, Report No R 6078-2, Contract No AF 33(616)-73272, 76p, AD 618 516, June 1965, Rocketdyne, Canoga Park, California.

42. Space Technology Laboratories, Inc, Reliability Growth of U.S. Rockets, Vol II, prepared for NASA/MSFC under Contract No NAS 8-11037, May 1964, SECRET.

43. Virene, E.P., Reliability Growth and the Upper Reliability Limit, How to Use Available Data to Calculate, Report No D2-24142-1, 31p, AD 804 150, December 1966, Boeing Company, Seattle, Washington. Also Reliability Growth and Its Upper Limit, Proceedings of 1968 Annual Symposium on Reliability, (IEEE Catalog No 68 C 33-R), 265-270, January 1968.

44. Weiss, George H., Discussion of the Paper by Dr. Wolman, in Marvin Zelen (ed.), Statistical Theory of Reliability, 163-164, University of Wisconsin Press, Madison, Wisconsin.

45. Weiss, H.K., An Analytical Model of Reliability Growth Through Testing, Report No 54 304, 17p, AD 035 767, May 1954, Northrop Aircraft Inc., Hawthrone, California.

46. Weiss, H.K., Estimation of Reliability Growth in a Complex System With a Poisson-Type Failure, Journal of the Operatioons Research Society of America, Vol 4, 532-545, 1956.

47. Wolman, William W., Problems in System Reliability Analysis in Marvin Zelen (ed.), Statistical Theory of Reliability, 149-160 University of Wisconsin Press, Madison, Wisconsin.

48. Zehna, P.W., Estimating Mean Reliability Growth, Report No NPS RP-60, 27p, AD 629 381, January 1966, Naval Postgraduate School, Monterey, California.

* Bibliography on Reliability Growth, appendix to; Crow, Larry H., Reliability Growth Modeling, U.S. Army Material System Analysis Activity, Aberdeen Proving Ground, MD. Technical Report No 55, 1972.

\# Reports added to this Bibliography by this author.

APPENDIX B

A REVIEW OF SOME RELIABILITY GROWTH MODELS*

This appendix describes a number of reliability growth models which are currently available. Each model is briefly described including the basic assumptions that were made in deriving the models. Technical references are given for each of these models where a more complete discussion of the model may be found.

Model 1. Lloyd and Lipow (see Appendix B, Reference 28) introduced a reliability growth model for a system which has only one failure mode. For each trial it is assumed that the probability is a constant that the system will fail if the failure mode has not been previously eliminated. If the system does not fail, no corrected action is performed before the next trial. If the system fails, then an attempt is made to remove the failure mode from the system. The probability of successfully removing the failure mode is also assumed to be a constant for each attempt. They show that the system reliability, R_n, on the n-th trial is

$$R_n = 1-Ae^{-C(n-1)}$$

where A and C are parameters.

Model 2. Another reliability growth model was considered by Lloyd and Lipow (see Appendix B, Reference 28) where the development program is conducted in K stages and on the i-th stage a certain number of systems are tested. The reliability growth function considered was

$$R_i = R_\infty-\alpha/i,$$

where R_i is the system reliability during the i-th stage, R_∞ is the ultimate reliability as $i \to \infty$ and $\alpha > 0$ is a parameter. Maximum likelihood and least squares estimates of R_∞ and α are given by Lloyd and Lipow

* Ref: Crow, Larry H. Reliability Growth Modeling, US Army Material System Analysis Activity, Aberdeen Proving Ground, MD, Tech Rpt 55, 1972.

along with a lower confidence limit for R_K.

Model 3. Weiss (see Appendix B, Reference 41) considered a reliability growth model where the mean time to failure of a system with exponential life distribution is increased by removing the observed failure modes. In particular, he showed that when certain conditions hold, the increase of the mean time to failure is approximately at a constant percent per trial. That is, if $\theta(i)$ is the mean time to failure of the system at trial i then $\theta(i)$ may be approximated under certain conditions by

$$\theta(i) = Ae^{Ci},$$

where A and C are parameters. Note that

$$\theta(i+1) = e^{C}\theta(i).$$

The maximum likelihood estimates of A and C are given by Weiss.

Model 4. Wolman (see Appendix B, Reference 42) considered a situation where the system failures are classified according to two types. The first type is termed "inherent cause" and the second type is termed "assignable cause". Inherent cause failures reflect the state-of-the art and may occur on any trial while assignable cause failures may be eliminated by corrective action, never to appear again. Wolman assumed that the number of original assignable cause failures is known and that whenever one of these modes contribute a failure, the mode is removed permanently from the system. Wolman uses a Markov-chain approach to derive the reliability of the system at the n-th trial when the failure probabilities are known.

Model 5. Barlow and Scheuer (see Appendix B, Reference 3) considered a nonparametric model for estimating the reliability of a system during a development program. They assumed that the design and engineering changes do not decrease the system's reliability, but, unlike some other models, they do not fit a prescribed functional form to the

reliability growth. Their model is similar to Wolman's in that each failure must be classified either as inherent or assignable cause.

It is further assumed that the development program is conducted in K stages, with similar systems being tested within each stage. For each stage, the number of inherent failures, the number of assignable cause failures and the number of successes are recorded. In addition, they assumed that the probability of an inherent failure, q_0, remains the same throughout the development program and that the probability of an assignable cause failure, q_i, in the i-th stage does not increase from stage to stage of the development program. The authors obtained the maximum likelihood estimates of q_0 and of the q_i's subject to the condition that they be nonincreasing. A conservative lower confidence bound for the reliability of the system in its final configuration was, also, given.

Model 6. Virene (see Appendix B, Reference 38) considered the suitability of the Gompertz equation

$$R = ab^{c^t},$$

$0 < b < 1$, $0 < c < 1$, for reliability growth modeling. In this equation a is the upper limit approached by the reliability R as the development time $t \to \infty$. The parameters a, b and c are unknown. Virene gave estimates of these parameters and demonstrated by examples the application of this model.

Model 7. Duane (see Appendix B, Reference 17) considered a deterministic approach to reliability growth modeling. He analyzed data available for several systems developed by General Electric in an effort to determine if any systematic changes in reliability improvement occurred during the development programs for these systems. His analysis revealed that for these systems, the cumulative failure rate versus cumulative operating hours fell close to a straight line when plotted on log-log

paper. The cumulative failure rate appeared to decrease at approximately the -0.4 or -0.5 power of cumulative operating hours.

The types of systems investigated were of the complex electro-mechanical and mechanical nature. Duane concluded that a line with a slope of -0.5 representing cumulative failure rate as a function of cumulative operating hours on log-log paper would probably be suitable for reflecting reliability growth for similar type systems developed at General Electric.

Mathematically, Duane's failure rate equation may be expressed by

$$\lambda(T) = KT^{-\alpha},$$

$K > 0$, $0 \leq \alpha \leq 1$, where $\lambda(T)$ is the cumulative failure rate of the system at operating time T, and K and α are parameters. It follows then that

$$\lambda(T) = \frac{E(T)}{T}$$

where E(T) is the expected number of failures the system will experience during T units of operation. This yields

$$E(T) = KT^{1-\alpha}.$$

Furthermore, the instantaneous failure rate at T is given by

$$\theta(T) = (1-\alpha)KT^{-\alpha}.$$

For a system with a constant failure rate the mean time between failure (MTBF) of the system at operating time T is in unit hours

$$M(T) = [\theta(T)]^{-1} = [(1-\alpha)K]^{-1}T^{\alpha}.$$

That is, the change in system MTBF during development is proportional to T^{α}.

With this notation $\alpha = 0.5$ closely represented the types of systems considered by Duane.

Model 8. Pollock (see Appendix B, Reference 32) considered a Bayesian reliability growth model for a system undergoing development. The parameters of the model are assumed to be random variables with appropriate prior distribution functions. Using his results, one may project the system reliability to any time after the start of the development program without data and, also, estimate the system reliability after data have been observed. He further gave precision statements regarding the projection and estimation.

Model 9. Barlow, Proschan and Scheuer (see Appendix B, Reference 2) considered a reliability growth model which assumes that a system is being modified at successive stages of development. At stage i the system reliability (probability of success) is p_i. The model of reliability growth under which one obtains the maximum likelihood estimates of $p_1, p_2, \ldots, p_K$ assumes that

$$p_1 \leq p_2 \leq \cdots \leq p_K.$$

That is, it is required that the system reliability be not degraded from stage to stage of development. No particular mathematical form of growth is imposed on the reliability. In order to obtain a conservative lower confidence bound on p_K, it suffices to require only that

$$p_K \geq \max_{i<K} p_i.$$

That is, it is only necessary that the reliability in the latest stage of development be at least as high as that achieved earlier in the development program.

Data consist of x_i successes in n_i trials in stage i, $i=1,\ldots,K$.

A variation of this model is treated in Barlow and Scheuer (see Model 5). In that model two types of failure, inherent and assignable cause, are distinguished.

Model 10. Another reliability growth model considered by Barlow, Proschan and Scheuer (see Appendix C, Reference 2) assumed that at stage i of development the distribution of system life length is F_i. The model of reliability growth under which the maximum likelihood estimates of $F_1(t), F_2(t), \ldots, F_K(t)$ are obtained, writing

$$\bar{F}_i(t) = 1-F_i(t)$$

is

$$\bar{F}_1(t) \leq \bar{F}_2(t) \leq \ldots \leq \bar{F}_K(t)$$

for a fixed $t \geq 0$. In order to obtain a conservative upper confidence curve on $F_K(t)$ and thereby, a conservative lower confidence curve on $\bar{F}_K(t)$ for all non-negative values on t, it suffices only to require that

$$\bar{F}_K(t) \geq \max_{i<K} \bar{F}_i(t)$$

for all $t \geq 0$. That is, the probability of system survival beyond any time t in the latest stage of development is at least as high as that achieved earlier in the development program.

Data consist of independent life length observations $X_{i1}, \ldots, X_{in_i}, i=1, \ldots, K$.

Model 11. Barlow, Proschan and Scheuer (see Appendix C, Reference 2), also, considered a reliability growth model which assumes that the system life at the i-th stage of development has increasing failure rate

Because of improvement from stage to stage

$$r_1(t) \geq r_2(t) \geq \ldots \geq r_K(t)$$

for $t \geq 0$, where $r_i(t)$ is the failure rate at time t at the i-th stage of development. That is, for each $t \geq 0$, the probability of system failure in the interval $(t, t+dt)$, given survival till time t, does not increase from stage to stage of the development program.

Given life-length observations, $X_{i1}, X_{i2}, \ldots, X_{in}$, the maximum likelihood estimates of $r_1(t), r_2(t), \ldots, r_K(t)$ are obtained.

LIST OF REFERENCES

1. Staats, Elmer B., "Acquisition Management Needs Realistic Forecasting to Close the Confidence Gap," Defense Management Journal, p. 21, April 1976.

2. Packard, David, "Improving R & D Management Through Prototyping," Defense Management Journal, p. 2, July 1972.

3. Naval Material Command, MTBF-Reliability Study Report, RADM K. R. Wheeler, May 1972.

4. U. S. Air Force, Minutes of Air Force Reliability Implementation Group Meeting, December 1973.

5. Packard, David, "Improving R & D Management Through Prototyping," Defense Management Journal, p. 5, July 1972.

6. Hollister, Floyd H., CDR USN, and Shorey, Russel R., "Design to Cost: Concept and Application," Defense Management Journal, p. 8, July 1973.

7. Amstradter, Bertram L., Reliability Mathematics, p. 3, McGraw-Hill, 1971.

8. Willoughby, Willis J., "Reliability by Design, Not by Chance," Defense Management Journal, p. 13, April 1976.

9. Department of the Navy, Harpoon Weapon System Request for Quotation, N00019-71-Q-001, Vol. 4, January 1971.

10. Department of the Navy, Model VFAX Airborne Weapon System, TS-169, Appendix C, (no date).

11. Department of the Navy, Request for Advanced Surface Missile System, N00017-68-R-2014, Vol. 4, May 1968.

12. Codier, Ernest O., "Reliability Prediction--Help or Hoax?" 1969 Annual Symposium on Reliability, p. 384, January 1969.

13. Duane, J. T., "Learing Curve Approach to Reliability Monitoring," IEEE Transactions of Aerospace, Vol. 2, No. 2, p. 536, April 1964.

14. Parker, Robert N., "R&D Emphasis on Reliability," Defense Management Journal, p. 19, April 1976.

15. Marsh, Robert T., Lt Gen U. S. Air Force, "Avionics Equipment Reliability, An Elusive Objective," Defense Management Journal, p. 24, April 1976.

16. Amstradter, Bertram L., Reliability Mathematics, p. 222, McGraw-Hill, 1971.

17. Barlow, Richard E. and Schever, Ernest M., "Reliability Growth During a Development Testing Program," Technometrics, Vol. 8, No. 1, p. 53, February 1966.

18. Jayachandran, Toke and Moore, Louis R., "A Comparison of Reliability Growth Models," IEEE Transactions on Reliability, Vol. R-25, No. 1, p. 49, April 1976.

19. Kreuze, F. J., "Growth Curves--A Practical Management Tool," 1972 Annual Reliability and Maintainability Symposium, p. 430, January 1972.

20. Amstradter, Bertram L., Reliability Mathematics, p. 220, McGraw-Hill, 1971.

21. Malvern, Donald, "The F-15A Eagle Program," Defense Management Journal, p. 40, April 1976.

22. Scanlan, Joseph A., "The TOW Weapon System," Defense Management Journal, p. 35, April 1976.

23. Allen, R. J., Fondon, M. C. and Hardy, C. A., "F-111A Reliability," 1970 Annual Symposium on Reliability, p. 128, January 1970.

24. Hinely, J. T. and Stovall, F. A., "C-141A Reliability Program," 1968 Annual Symposium on Reliability, p. 288, January 1968.

25. Cox, Tony D. and Keely, John, "Reliability Growth Management of SATCOM Terminals," 1976 Annual Reliability and Maintainability Symposium, p. 218, February 1976.

26. Bear, J. C., "Approach to Reliability for the SM-2 Missile," 1973 Annual Reliability and Maintainability Symposium, p. 79, January 1973.

27. Telephone conversation, J. C. Bear, General Dynamics, Pomona, Calif., 31 August 1976.

28. Telephone conversation, Mr. Hillman, U.S. Army Missile Command, Huntsville, Ala., 31 August 1976.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Library, Code 54 Department of Administrative Sciences Naval Postgraduate School Monterey, California 93940	1
4.	Professor J. W. Creighton, Code 54Cf Naval Postgraduate School Monterey, California 93940	40
5.	Mr. Ronald G. Anderson 810 Brently Avenue Camarillo, California 93010	2